

Wireless Technology Use Case Requirement Analysis for Future Space Applications

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Abstract

This report presents various use case scenarios for wireless technology -including radio frequency (RF), optical, and acoustic- and studies requirements and boundary conditions in each scenario. The results of this study can be used to prioritize technology evaluation and development and in the long run help in development of a roadmap for future use of wireless technology. The presented scenarios cover the following application areas: (i) Space Vehicles (manned/unmanned), (ii) Satellites and Payloads, (iii) Surface Explorations, (iv) Ground Systems, and (v) Habitats. The requirement analysis covers two parallel set of conditions. The first set includes the environmental conditions such as temperature, radiation, noise/interference, wireless channel characteristics and accessibility. The second set of requirements are dictated by the application and may include parameters such as latency, throughput (effective data rate), error tolerance, and reliability. This report provides a comprehensive overview of all requirements from both perspectives and details their effects on wireless system reliability and network design. Application area examples are based on 2015 NASA Technology roadmap with specific focus on technology areas: TA 2.4, 3.3, 5.2, 5.5, 6.4, 7.4, and 10.4 sections that might benefit from wireless technology.

Nomenclature

b/s	=	bit per second
dB	=	decibel
E_b	=	energy per bit
G	=	giga
Hz	=	Hertz
k	=	kilo
K	=	temperature unit in Kelvin
M	=	mega
N_0	=	noise power spectrum density
S	=	Sample
s	=	second

I. Introduction

This report integrates input from 2015 NASA Technology Roadmap¹, NASA Technical reports, and recent developments in wireless communications research area as relates to space applications. An introduction to wireless communications and networking area including both sensing and communications applications is presented in this section. Basic definitions of parameters characterizing a wireless system is also defined in this section. One of the widely used family of wireless standards is IEEE 802, which includes 802.11² (used in WiFi), 802.15.1³ (Bluetooth), and 802.15.4⁴ (ZigBee). Due to high consumer demand for WiFi and Bluetooth devices and industry

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need for ZigBee networks, necessary components to build a working system can be obtained at low cost with high reliability. This includes transceiver chips, break out boards, interfaces, and antennas. The down side of using popular technologies such as IEEE 802.11 (WiFi) is interference caused by increasing number of users, devices, and demand for bandwidth. Although, WiFi has 14 channels to scan and choose the least crowded one, but in reality only 3 of those channels are non-overlapping and truly interference free at any given time⁵ (fig. 1).



Figure 1. Illustration of 14 available and 3 non-overlapping (at any specific time) WiFi channels.

Some other members of this family of standards are 802.15.3⁶ (high data rate WPAN: wireless personal area network) and 802.16⁷ (WiMAX). The former is faster version of ZigBee for applications that require higher throughput such as video transport network, while the latter is used for mobile and fixed high speed access at long ranges. WiMAX is not well adopted in the US, where LTE (Long term evolution) and LTE-A (advanced) are currently used with LTE-U (unlicensed) scheduled to hit the market in near future. WiMAX is heavily used in India and a slightly modified version called WiBro was rolled out in South Korea. The main differences between WLAN (Wireless Local Area Network) standards such as WiFi and WPAN standards such as ZigBee are: Power consumption; Coverage; Device type; and Network lifetime. WLAN has much larger lifetime, coverage area, and consumes more power as compared to WPAN, which is often deployed for a short period of time using simple and low power devices. More details on Bluetooth and ZigBee protocols based on IEEE 802.15 family of standards are presented next.

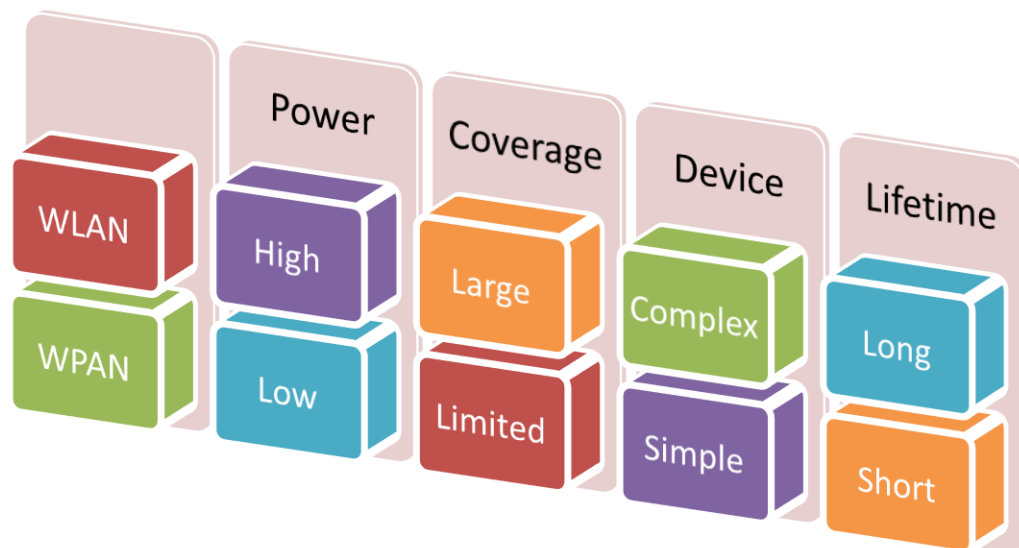


Figure 2. Comparison between WLAN and WPAN.

A. Bluetooth Physical Layer and Interference Challenges

Bluetooth physical layer is based on IEEE 802.15.1, operating at 2.4 GHz using Frequency Hopping (FH) scheme and can achieve 1 MS/s with Gaussian Binary frequency shift keying modulation (GFSK). Resource sharing is managed using time domain duplexing (TDD) and its effective one-way data rate is 732.2 kb/s. This is achieved with 0 dBm transmit power over a 10 m range. Increasing the power to 20 dBm extends the range to 100m for long range applications. Data delivery is protected against error and packet loss using forward error correction codes of rate 1/3 and 2/3 and automatic retransmission request (ARQ) in a fast unnumbered manner. Two way 128 bit authentication and 128 bit payload cipher is complimented with a PIN based user initiated process for added security.

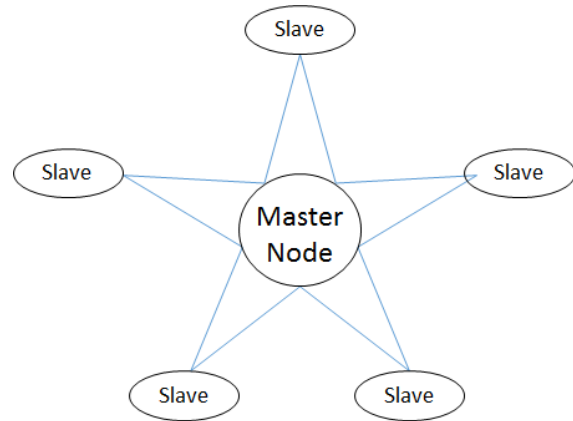


Figure 3. Bluetooth Master-slave structure.

Networking of up to 7 active or 200+ inactive devices connected to a single Master node is provisioned in the standard. The main concern when using WPAN 802.15.1 in presence of infrastructure based WLAN 802.11 (WiFi) is interference. WPAN hops into 22 out of 79 sub-channels used by WLAN. This causes the WLAN to experience interference too, hence increasing temporal duration of its packets, which in turn causes more and more interference to WPAN leading to less and less data rate for both networks. This interference problem between WPAN and WLAN may be addressed in multiple ways. The first order approach is for WLAN to avoid 24 sub-channels (including two adjacent to the 22 used by WPAN), but that leads to fixed decrease in throughput and increase in latency. Several collaborative and non-collaborative coexistence mechanism such as Alternating wireless medium access (AWMA), packet traffic arbitration (PTA), and deterministic interference suppression (DIS) have been proposed in the literature to address this issue. For more details on these methods refer to IEEE standard 802.15.2⁸.

B. ZigBee Physical Layer and Its Applications

ZigBee physical layer is based on IEEE 802.15.4, operating at 868 MHz, 915 MHz, and 2.4 GHz at 20, 40, and 250 kb/s rates with 1, 10, and 16 available channels, respectively. The lower frequency bands utilize binary phase shift keying (BPSK) and direct sequence spread spectrum (DSSS) with differential encoding and raised cosine pulse shaping, while the higher frequency band communicates 32 chips PN sequences using offset quadrature phase shift keying (OQPSK) modulation and half-sine pulse shaping. Transmit power of -3 dBm provides a low power short range (few 100 ft) networking that can support mesh and ad hoc networking. Both secure (7 security suites are available) and unsecured operation modes are available. Secure mode include authentication and key establishment, access control list, data encryption, and frame integrity. Resources are shared the medium access control layer (MAC) using carrier sense multiple access with collision avoidance (CSMA/CA) and random back off timer.

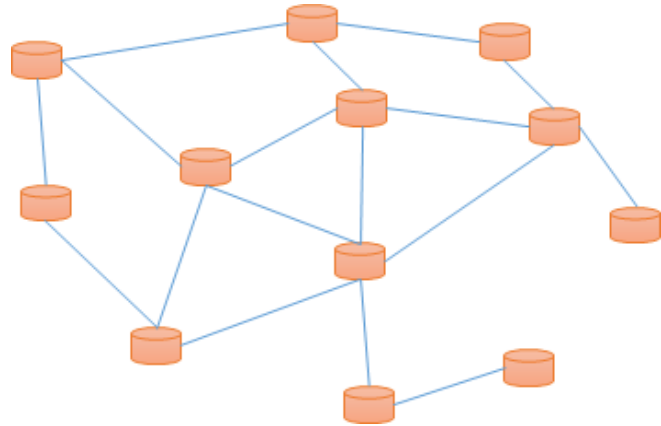


Figure 4. ZigBee mesh network structure.

ZigBee supports mesh networking and is scalable to a large network with the following provisions. The data sampling rate should be kept to a minimum in networks with large number of sensors to minimize the effect of interference/collisions, which may prevent nodes from finding open slots in the network for transmitting their packets. The number of hops between information source and network sink or data processing center should also be

kept to a minimum to preserve data quality and avoid unbalanced power consumption in the network. It should be noted that nodes at the edge of the network needs to be designed with different capabilities and resources as compared to the ones in the center. High data rate WPAN and WiFi have similar characteristics and mainly used when power consumption is not limited and high data rates are required. Portable devices (that can be moved but needs to be normally plugged in) mostly use these standards as compared to mobile devices that often use low power solutions such as ZigBee and Bluetooth. Therefore, this section does not elaborate more on 802.15.3 and 802.11 and refers the reader to IEEE standards.

C. Basic Parameters of a Wireless System

Power consumption and bandwidth requirements are the first parameters that come to mind when reviewing requirements of a wireless application. However, in order to evaluate performance and reliability of wireless systems in a network setting more detailed parameters need to be considered. In a point to point analog communication link, the main measure of channel quality or link reliability is signal to noise ratio (SNR). This parameter can be augmented to include interference in a networked environment (SINR). Modern digital communication systems have replaced conventional analog systems in recent years due to their high spectrum and power efficiency. Therefore, the focus of this section will be on performance indicators of digital communication systems. Each data source needs to be sampled and digitized before entering a digital wireless system. The information content of the source or bandwidth of the analog signal dictates sampling rate, and accuracy requirements guide the digitization resolution. For instance, phone quality voice with 4 kHz bandwidth sampled at 8 kHz and quantized with 8 bits/sample renders a 64 kb/s digital stream at the input of a wireless communication system. This digital data can be compressed (source coding) to remove redundancy and then encoded (channel coding) to be protected against noise and interference and modulated using a high frequency (RF) signal for longer range transport in the network. The first parameter for performance evaluation of such a system is called BER or bit error rate. For example, 3 bits error in a million bit stream results in $BER = 3E-6$. In multiuser networked systems, collision may occur, which can cause packet loss (PL). This is another parameter used for performance evaluation of a networked system. Environmental conditions and settings that a wireless system is designed for can yield to modeling the stochastic wireless channel using some of the widely used channel models. This allows for BER and PL estimation using simulation tools such as MATLAB (Mathworks Inc.) before a system is implemented and tested. Additive White Gaussian Noise (AWGN) channel is the most widely used model in fixed networks. In mobile networks with multipath fading and several scattered signal beams, Rayleigh channel model is a good fit. Adding a strong line of sight to the scattered signals, Rician model becomes a better fit. Depending on the application scenario, environmental conditions, and users' location and behavior one of these models may be preferable over the others. An example is provided in the figures below, where the standard ZigBee system is enhanced by adding an optimized error correction code. BER performances are evaluated over AWGN (left) and Rayleigh fading (right) channels⁹. This shows how significant reliability can be achieved at very low cost.

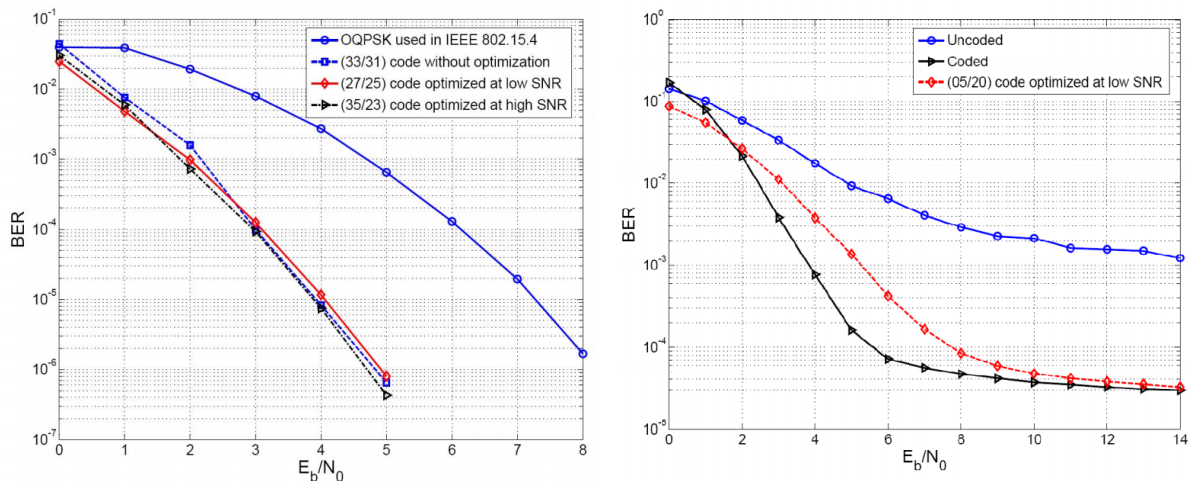


Figure 5. BER Performance of un-coded IEEE 802.15.4 and coded version with optimized error correction code over AWGN (left) and Rayleigh Fading (right) channels.

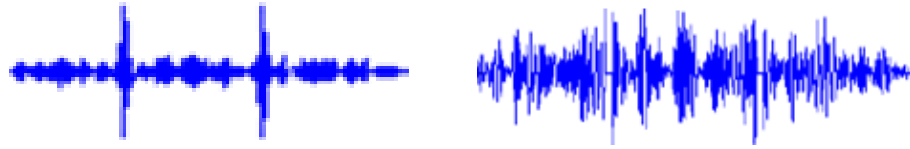


Figure 6. Responses of a single passive sensor (left) vs aggregate response of multiple passive sensors (right).

Measuring reliability of a wireless network not only depends on reliability of each individual link, but also on the network ability to manage interference. Another example is provided to demonstrate how to measure reliability of a passive wireless sensor network by looking at the aggregate interference. Figure 6 shows a single sensor response (left) with main information in the two peaks locations and aggregate response of multiple sensors (right) where peaks are not easy to detect any more being buried in side lobes.

To measure the reliability of a single link, a new parameter such as peak to side-lobe ratio (PSLR) may be defined much like signal to noise ratio in analog communication links. The higher the PSLR, the lower the chance of losing peak locations in multi-sensor response in a network. Extending this concept to network reliability measurement, ratio of PSLR to absolute power of side-lobes (on average or to be conservative on maximum sense) determines how many sensors can operate in such a network with acceptable reliability without any interference cancellation. Methods such as the one presented in¹⁰ may be used for managing the interference, hence increasing the number of sensors in such a network.

II. Use Case Scenarios and Environmental Requirements

This section introduces space related use case scenarios that may benefit from wireless technology. These include (i) Space Vehicles (manned/unmanned), (ii) Satellites and Payloads, (iii) Surface Explorations, (iv) Ground Systems, and (v) Habitats. Some common environmental conditions to space applications according to a recent study at NASA MSFC include¹¹: High Radiation (10krad – 1Mrad); Cryogenic Temperatures (H₂: 20K; O₂: 90K; CH₄: 112K); High Temperatures (400K-3000K); and Harsh chemical environments. Each use case scenario and its specific boundary conditions relevant to wireless system design are presented next.

A. Space Vehicles

Space vehicles operate in extreme conditions with notable vibrations on their various sub-systems, which might exclude or limit usage of specific types of sensors and electronics such as micro-electro-mechanical systems (MEMS). Monitoring critical systems such as thermal and pressure systems, cryogenic fluid management, Heating Ventilation and Air Conditioning (HVAC), Environmental Control and Life Support System (ECLSS), Lighting Monitoring, Docking, and Rendezvous systems require specific considerations as follows. Most of these systems are in hard to reach areas that are not easily accessible. The wireless system design need to accommodate operations in confined spaces and often closed metallic chambers or sometimes even inside fluid environments at cryogenic temperatures (wireless acoustic or low frequency magnetic coupling might be considered in these situations). A recent work at NASA MSFC demonstrated proof of concept for wireless sensing inside a fuel tank¹². Monitoring the engine and heat shield requires sensors that can operate in high temperature environments with harsh chemical vapors present. Constant monitoring of pressure and temperature at various locations of the engine can assist in real-time performance measurement and dynamic performance control using sensors and actuator networks. Usage of RF signals and electronics in close proximity of fuel lines and tanks in launch vehicles should be reviewed from safety point of view to avoid any potential case of RF waves heating up fuel or causing sparks or premature ignitions. This is not a critical concern and can be avoided by careful design, placement and insulations.

Challenges:

- Wide range of temperature variations and Vibration tolerance
- Accessibility in confined environments
- Signal propagation in metallic enclosures

Benefits:

- Acquiring more data from supporting structures and engine itself
- Reducing weight due to cable elimination
- Dynamic performance control with wireless sensing and actuation

B. Satellites and Payloads

Satellites and payloads operate in harsh environment and often require monitoring and protection against extreme temperature changes and radiation. Whether using radiation hardened hardware or adding internal heaters or coolers to keep the equipment in desirable environmental condition, it is necessary to monitor the internal temperatures and radiation doses at all times. Although, it may not make sense to replace a short few cm wire inside a small satellite with wireless, for some applications where drilling a hole in the payload or satellite's exterior body may lead to loss of heat and energy, short range magnetic coupling wireless solutions will become important. Other applications include monitoring external solar arrays for MMOD impact or damage evaluation as well as transferring power between two disjoint sections.

Challenges:

- Wide range of temperature and radiation variations
- Size and weight limitations
- Signal propagation in metallic enclosures
- Power constraints

Benefits:

- Wireless connection between two disjoint sections
- Reducing heat loss by avoiding drilling holes
- More efficient use of harvested power

C. Surface Explorations

Autonomous exploration of planetary surfaces may require machine vision and robotics arms to recognize various object types and manipulate them, drill ground to collect soil samples, and navigate to return samples to the base. All these applications can benefit from wireless sensors. For instance, Infrared sensors can be used alongside visible light cameras for object detection and classification and assisting the robotics arms to maneuver accurately. Humidity and temperature sensors can be used during ground drilling, while vibration sensors can monitor the drill operation. Navigation without Global Positioning System (GPS) on planetary surfaces requires dedicated active wireless links with precise time of arrival measurements (e.g. one example is the ultra-wide-band (UWB) radios developed at NASA JSC¹³). Other techniques such as passive radio frequency identification (RFID) tags and readers may also be used to find assets in known areas pre-marked with tags.

Challenges:

- Capability to operate and survive dust or radiation storm
- Mobile chemical and biological sensor units
- Long range reliable link back to base with navigation capabilities

Benefits:

- In situ testing of samples
- Navigation without need for GPS
- Dynamic control of robotic arms using wireless sensors and actuators

D. Ground Systems

Ground testing often requires structural sensors such as strain gauges, accelerometers, and deflection sensors. Testing fuel tanks may require leak detection sensors, hydrogen (or other gas) sensors, humidity, and temperature sensors. Performance tests are conducted in controlled environment with thermal cycles that mimic space conditions. Therefore, all these instrumentation, although used on earth, need to be capable of operating in harsh environments. Wiring and cabling may be cumbersome, costly, or may be infeasible in some cases. Therefore, wireless sensing in ground system can open up lots of new opportunities to gather critical data.

Challenges:

- High precision in sampling and data transfer
- Interference management among large number of sensors sending data
- Working within limitations of test setup at specific distances

Benefits:

- Acquiring more data for structural analysis that is not possible using wires
- Reducing cost of tests due to cabling elimination
- Flexibility of test for adding more sensors later without redesigning the whole wiring plan
- Versatility in programming test beds for future tests

E. Habitats

Autonomous monitoring of habitats, living conditions, and inventory tracking are the main use case scenarios that can benefit from wireless technology. RFID based inventory tracking methods for autonomous logistical management (ALM) is being developed at JSC and can tie into the habitat monitoring itself. Integrating sensors as load on RFID devices and reading the changes in the response in addition to ID numbers is a promising approach in this direction. Monitoring living conditions including physical (temperature, humidity, and radiation), chemical (air and water quality) and biological (mold and mildew or other airborne bacteria) are some critical applications that benefits from wireless sensors. Another important aspect of monitoring habitat systems is evaluating cognitive changes of its inhabitants, i.e. crew health monitoring. Real time vital signs tracking and wireless sensors for sleep behavior monitoring are essential for ensuring mission success. For more info on habitat systems refer to section 3.6 in this report.

Challenges:

- Wide range of temperature and radiation variations
- Aggregation challenges in multi modal sensor data with different sampling rates and precisions
- Signal propagation in metallic enclosures

Benefits:

- Acquiring more data from habitat structure
- Reducing weight due to cable elimination
- Flexibility of change in design and sensor location after the deployment

III. Application Specific Requirements

In this section application specific requirements from data transport and reliability points of view are studied. Application area examples are based on 2015 NASA Technology roadmap with specific focus on the following technology areas: TA 2.4, 3.3, 5.2, 5.5, 6.4, 7.4, and 10.4 sections that might benefit from wireless technology¹. Each section starts with the definition of the technical area followed by discussion of current and future technologies that might benefit this area.

A. TA2.4: Engine Health Monitoring

“TA2.4.1: Use of simulation and data processing to determine and mitigate operational, safety, and reliability risks and issues in the propulsion system. In general, the key metrics for health monitoring for in-space propulsion are reliability, weight, and cost.”

This technology area is closely connected to section 2.1 on this report titled: Space Vehicle. A combination of wireless solutions such as RF, optical, and Acoustic may be needed to cover all subsystems of a space vehicle in a reliable manner. Most sensors used in these applications such as temperature, pressure, fuel level, and gas sensors are low data rate with the exception of engine health monitoring, which requires high speed sampling of accelerometers or load sensors. Operation in extremely low or high temperature may require specially coated material to withstand those temperatures. Some technologies such as SAW devices may be a good potential for these applications at extreme temperatures^{14,15,16,17}.

Video monitoring of environment for short duration events or monitoring vehicles for performance verification is also of interest in space applications. For example, a short video of landers thrusters sent to control station for verification purposes can help in improving design and real time performance adjustments. High data rate WPAN standards such as IEEE 802.15.3 are good standards suitable for these kind of applications.

B. TA3.3: Wireless Power Transmission

“TA3.3.4: This area describes needed enhancements in short-range, low power wireless power transmission for battery charging and instrumentation and in longer range, high power surface element applications.”

Wireless power transfer for remote operation of battery-less sensors has received recent attention. Either for short range applications (near field magnetic coupling) or longer range operations (RF energy harvesting), some commercial systems offer practical solutions. The transmitted power in both cases will be used to power a remote unit and get data for a short period of time. NASA MSFC in collaboration with JACOBS have demonstrated short and medium range systems based on commercial and custom made near-field coupling systems. Efficient antenna design with phased-array steering beam capabilities can be used to extend the range of such systems, while focusing the power more efficiently. Transmission scheduling is also another technique presented in this report that is capable of achieving longer lifetime for remotely communicating nodes for a fixed transferred power. The idea is based on the fact that wireless channel is not always reliable and occasionally packets are lost or received with errors beyond correction capabilities of the receivers. If the remote transmitter considers its current energy level and wireless channel condition to determine whether it is best to transmit or wait until next time slot, the harvested power will not be wasted on transmitting a packet with low chance of delivery. Simulation results demonstrate lower outage probabilities may be achieved if an acceptable channel threshold is used to guide decisions at the transmitter.

C. TA5.2: Radio Frequency Communications

“Radio Frequency (RF) Communications strives to dramatically accelerate techniques in use today for NASA’s missions. RF technology development concentrates on getting more productivity out of the constrained spectrum bands that are allocated to space users. Although it is quite a bit more mature than optical communications, there is still a great deal of promise for technology breakthroughs in the RF domain. The focus of RF technology development will be on the RF spectrum allocated and needed for space use by the International Telecommunication Union (ITU), where adequate bandwidth would provide a useful service, or where the application is beyond the near-Earth environment.”

Although spectrum-efficient and power-efficient technologies are separated into two categories in this technical area, they are not precluded from being used together in an integrated manner. If the propagation model is properly selected, spectrum efficient modulation and RF front end can be designed to take the most advantage of the channel. Power efficiency can be achieved in one layer below, i.e. the baseband of physical layer, where error correction codes can be used to achieve a desirable bit error rate with much less transmit power. All these sub-systems of an RF communication unit have to work seamlessly and efficiently with antenna system. Antenna needs to be efficient in terms of power transfer (matching circuitry), while it can play an integrated role in advanced coding schemes such as Space-time codes implemented over multiple-input multiple-output (MIMO) systems.

One recent hot research topic in RF communication is full duplex. Motivated by ever increasing demand for data rate and throughput, number of users/nodes, and limited spectrum and acceptable latency values, researchers are looking at new ways to increase the RF communication system capacity and achievable throughput. Current RF transceivers operate in half-duplex mode, meaning that they can not simultaneously transmit and receive on the same frequency band. The transmitter and receiver either transmit at different times or on different frequencies. The potential to use both time slots and frequencies to simultaneously transmit and receive is tempting researcher for an easy way to achieve double data rate. The challenge is the several orders of magnitude difference between transmitted and received signals, making it almost impossible for the receiver to detect low power received RF signal in presence of high power interfering transmitter signal. Highly accurate echo cancellation methods at antenna level, analog RF front end, and digital baseband levels need to work hand in hand to make full duplex a reality.

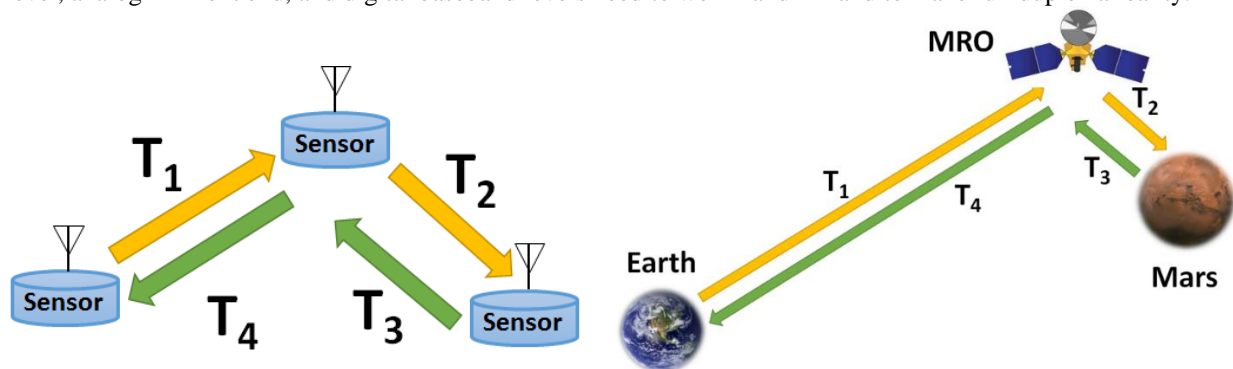


Figure 7. Four step packet exchange in traditional two way relay channel between wireless sensors (left) and Earth and Mars via MRO (right).

For deep space application, due to large distances between two communicating entities, latency is of critical importance. The full duplex method can potentially cut latency in half, enabling new applications and faster data exchange rates. Another method to double the throughput or cut the latency in half is called network coding. Due to large distances in space applications, exchanging data between two RF nodes often requires a relay and at least 4 time slots (fig. 5). As an example, Earth to Mars communication through Mars Reconnaissance Orbiter (MRO) is considered in this section.

The first time slot is used by the ground station to send its packet to the MRO (serving as relay) that will forward that data to Mars surface station in the second time slot. The same process is followed by Mars surface station to send its packet to earth via MRO. Network coding can be used to enhance throughput by a factor of two, when both Earth and Mars nodes send their data at the same time to the MRO to later broadcast the superimposed signals back to them. In this case, each node can extract the other packet using a simple mathematical operation. Network coding can be performed at network layer or physical layer. A simple XOR operation at the network layer can provide notable efficiency as compared to traditional two-way relay channels without network coding. However, significant throughput enhancement can be achieved if physical layer network coding is used¹⁸. This method is applicable to both deep space communication networks and short to medium range wireless sensor networks.

D. TA5.5: Cognitive Networks

“TA5.5.3: Cognitive Networks: Communications system in which each communications node on the network is dynamically aware of the state and configuration of the other nodes to autonomously optimize their operational parameters in response to changes in user needs or environmental conditions.”

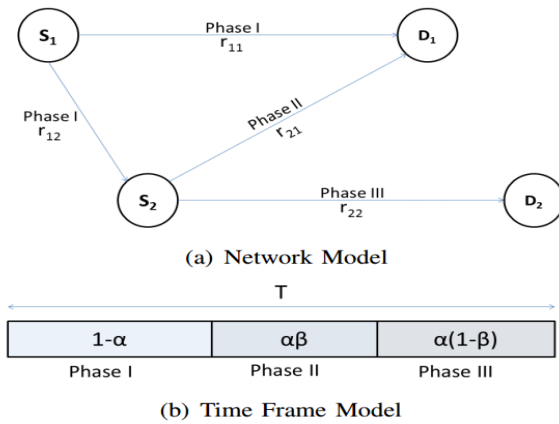


Figure 8. Network (top) and Time frame (bottom) model for cognitive cooperation scheme.

to send their data. Ensuring that a dedicated portion of time slot $(1-\alpha)$ is allocated to high priority users, guarantees their cooperation in this game theoretical resource allocation scheme. This combined cooperative and cognitive radio approach may be the key for future implementation of cognitive networks. Noting that complete interference alleviation is unavoidable, if high priority traffic from critical users are always prioritized over less sensitive traffic, low priority users can never get any data across. Cooperative relaying is the price that low priority users pay to gain access to the spectrum during a predetermined $(\alpha(1-\beta))$, but dynamic portion of each time slots.

E. TA6.4: Environmental Monitoring and Sensors

“TA6.4.1: Sensors: Air, Water, Microbial, and Acoustic: The objective of this area is to provide future spacecraft with advanced, networks of integrated sensors to monitor environmental health and accurately determine and control the physical, chemical, and biological environments of crew living areas and their environmental control systems.”

This section is closely connected to section 3.1 of this report. Sensors and wireless systems required for environmental monitoring inside the vehicle or habitats (see sections 2.1 and 2.5 of this report) can be designed with less stringent requirements as opposed to engine health monitoring system. The interior environment is mainly shielded from extreme thermal fluctuations and radiations, but pose other challenges such as multi-path reflections and scattering of wireless signals no matter if they are RF, acoustic, or even optical (which requires line of sight).

F. TA7.4: Habitat Systems

“TA7.4.1: Integrated Habitat Systems: Addresses acoustical treatments and noise reduction; solar optic lighting and heating; low-toxicity, fire-retardant textiles; antimicrobial and surface coatings; and embedded sensors that monitor system performance. Additional dependency technologies that support Integrated Habitat Systems capabilities are being developed under other technology areas, such as TA 4 Robotics and Autonomous Systems, TA 6 Human Health, Life Support, and Habitation Systems, TA 8 Science Instruments, Observatories, and Sensor Systems, TA 11 Modeling, Simulation, Information Technology and Processing, and TA 12 Materials, Structures, Mechanical Systems and Manufacturing.”



Figure 9. Exterior view (left) and inside view (right) of Inflatable lunar habitat (42 ft diameter 10 ft high concentric torus) designed and built by NASA JSC and instrumented with wireless sensors by University of Maine’s WiSe-Net Lab team.

This section is closely connected to section 2.5 of this report, where design requirements and environmental conditions of habitats are discussed. Figure 9 shows the outside and inside views of NASA’s inflatable lunar habitat, a 42 ft diameter concentric torus that is built by NASA JSC and instrumented by the University of Maine’s WiSe-Net laboratory researchers with 124 passive and 48 active sensors. These sensors monitor the structural integrity of the habitat. They localize impact, find leaks, and track temperature and humidity. The results are visualized on a tablet app with easy to view data using a multi-color heat map.

This example demonstrates what can be done with current technology when it comes to monitoring habitat systems. Other types of habitats such as the ones at NASA MSFC made of metal or wood (vs fabric) may require other modes of communications, being RF or acoustic or even optical depending on the use case. The interior size and shape of a metal cavity will determine the best frequency to use and what frequencies to avoid. The inflatable example is a great test-bed for technology demonstration as well as outfitting exercise including human factors perspective.

It is important that both wireless technology developers and human factor researchers work together when creating monitoring systems for habitats. Other monitoring needs in habitats that might benefit from wireless sensing are biological sensing of air and habitat interior to prevent bacteria growth on the interior walls due to condensation and chemical monitoring of air and water systems using wireless sensor for added spatial and temporal resolution without adding too many extra wires.

G. TA10.4: Sensors and actuators

“TA10.4.1: Sensors and Actuators: Nanotechnology-based sensors include systems for the detection of chemical and biological species to support planetary exploration and astronaut health, in addition to state (temperature, pressure, strain, damage) sensors for use in vehicle health management. Nanotechnology can lead to low-volume, less invasive sensors and actuators with better performance and lower power demand for new designs of morphing vehicle control surfaces, rovers, and robotic systems.”

Eliminating wires from sensors and actuators network will certainly presents significant savings in weight and cost. However, new challenges need to be overcome before this approach becomes a reality. Several applications of sensors and actuators requires a feedback control system to act on sensed data in a timely fashion and still remain

stable. Wireless feedback control systems with noise and delay in feedback link are studied recently²⁰. The effect of noise in the wireless channel is modelled using AWGN noise, while delay is assumed to be constant (a function of end to end wireless system delay). Preliminary results indicate that new controllers can be designed to operate satisfactorily in these environments as long as the noise and delay are below specific thresholds. This is an ongoing research area with more results to emerge soon. Although the focus of this technical area TA 10.4 is on nano-sensors, but it is noteworthy to mention that micro-sensors capable of detecting bio-chemical species are also a viable candidate to consider for sensor actuator networks. Technologies such as surface acoustic wave with thin film deposited on their exterior surface can be designed to be sensitive to a variety of physical, chemical, or biological substances.

IV. Implementation Roadmap

Depending on various applications and their operational environment, a specific wireless technology may be more desirable from power, spectrum efficiency, reliability, and cost points of view. This report also considers network architectures and their scalability (for future expansion) and flexibility (programmable and fault tolerance). Heterogeneous wireless networks with fall back provisions enhance the overall link reliability.

The future of space exploration is being built on space launch system (SLS) which is not designed for a specific mission, but rather for developing capabilities to be able to adopt to various deep space missions. It makes sense to develop a wireless sensing system with the same vision, not for a specific application, but rather with a modular design that can be tailored to various applications needs. Different radio technologies that were presented in this report, along with multiple sensor types, and various ways of powering them including some interfaces in between create a flexible architecture for data communication with no wire. Figure 10 shows an analogy with SLS. MSFC's approach to modular design that covers usability, applicability, and operability of transmission methods for different power methods and environments is depicted in Figure 11.

Table 1 summarizes potential technology areas that can impact the general five use case scenarios. Dark shaded squares indicate closely related technical areas and application use cases, while lightly shaded cells indicate potential benefit from wireless technology broadly defined.

Table 1. Potential technology areas that can impact different use case scenarios.

Use case \ Technology area	TA2.4 Engine Health	TA3.3 Wireless Power	TA5.2 RF Comm	TA5.5 Cognitive Networks	TA6.4 Environmental Monitoring	TA7.4 Habitat Systems	TA10.4 Sensors & Actuators
2.1. Space vehicles							
2.2. Satellites and payloads							
2.3. Surface explorations							
2.4. Ground systems							
2.5. Habitats							

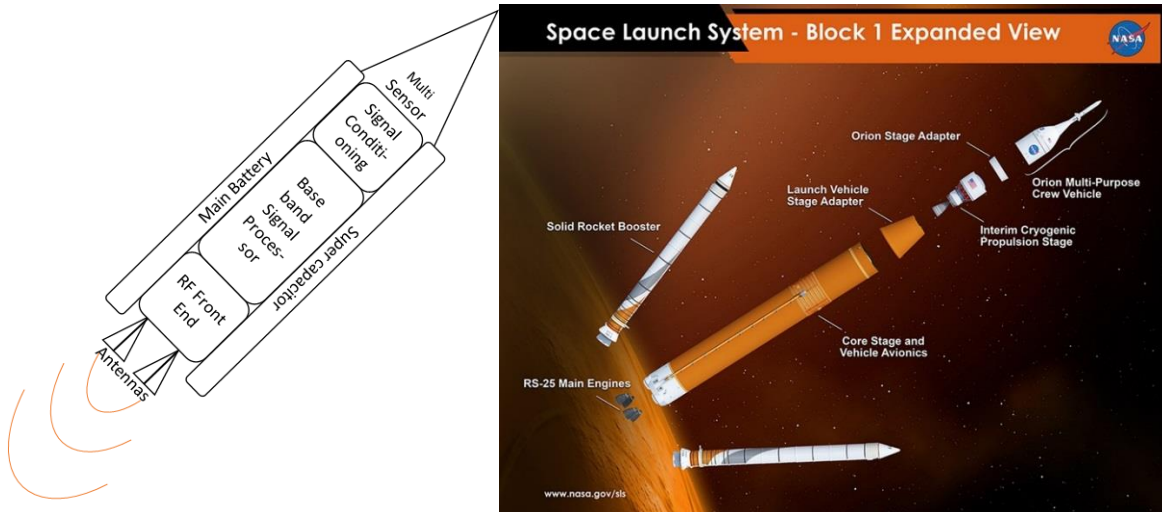


Figure 10. A modular flexible wireless system architecture that can be adapted to different missions by swapping antenna options, exchanging sensors, and reprogramming the baseband stage, while keeping the broadband RF front end and power system fixed. Very much similar to the concept of SLS that can be adapted to different missions.

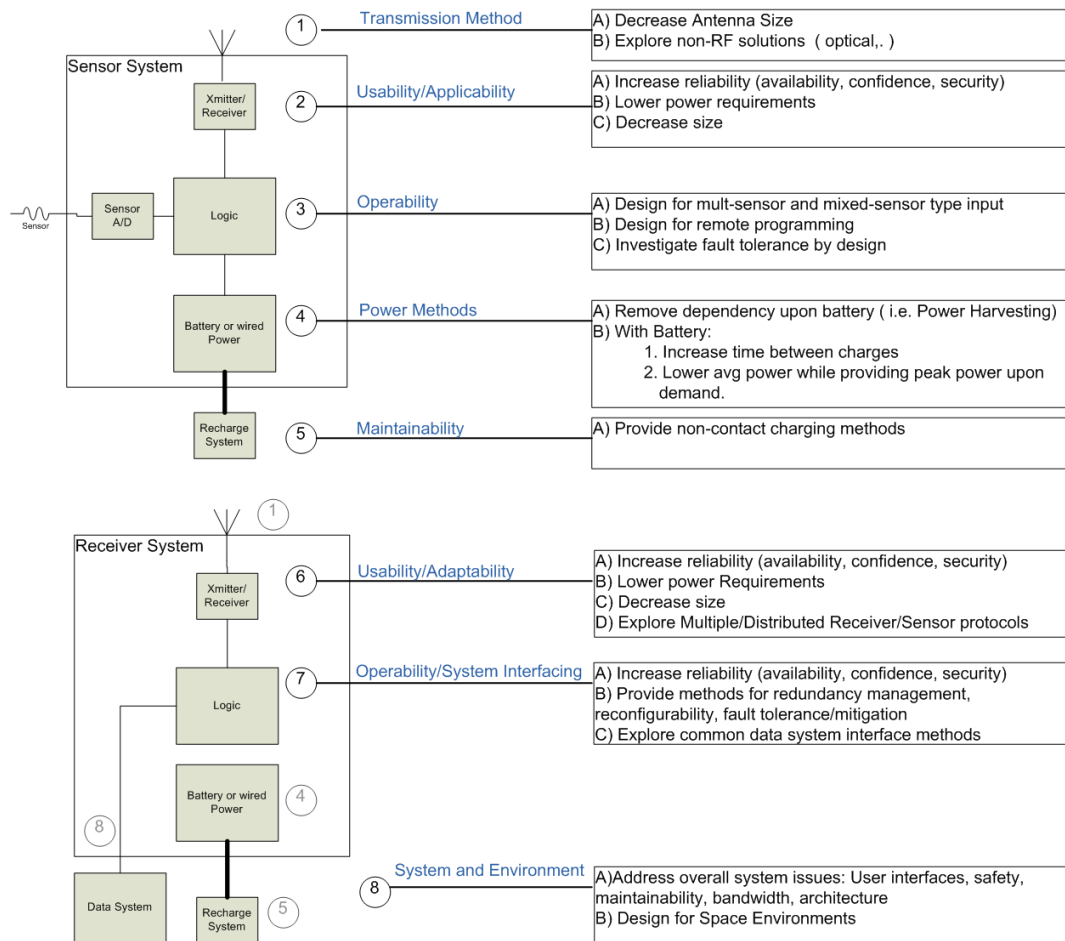


Figure 11. Current wireless interest areas at NASA MSFC.

Guided by Table 1, the current state of wireless communications networks in space applications and desired state in short and long term are summarized in the following roadmap (Table-2). Technology needs requiring less than 5 years to develop are labeled as short term. These include more mature technology areas such as scalability of networks with large number of sensors, and eliminating battery dependency through wireless power transfer or passive sensing as described in this report. Other technology areas which require more basic and applied research and development are categorized as long term with estimated 5-10 years development plan.

Table 2. Roadmap for Wireless Technology Development.

Where we are	Short term <5 Yr	Long term, 5-10 Yr	Where we want to go
1. Not space certified, rad tolerant or rad hard		X	1. Space certified
2. Low reliability		X	2. High reliability
3. Limited# of networked nodes	X		3. Large network sizes
4. Not scalable	X		4. Scalable
5. Not reconfigurable		X	5. Reconfigurable
6. Lack of coexistence in transmit protocols		X	6. Coexisting protocols with cognition
7. Battery dependent	X		7. Battery free

V. Conclusions and Future Directions

Wireless Technology has the potential to be used in space applications and provide unique capabilities that are not obtainable in wired systems. The space environment application areas are varied and each have a unique set of requirements that will require further development and maturation of wireless technology. Fortunately wireless technology in the commercial world is developing rapidly and the networking, management, reliability, and security techniques developed within this environment can be used as stepping stone for adopting this technology for space. Looking at the history of wireless can help in predicting the future direction and potential growth opportunities. The 1st generation of analog communication (AMPS) quickly turned into 2G (GSM/CDMA) or digital. The data rates were further improved when 3G (e.g. UMTS, HSPA and 1X-EV-DO) was introduced. The improvements continued with current 4G (LTE, LTE-A) standard very quickly. Some future directions in wireless communications industry motivated by exponential increase in demands include a wide array of new technologies under research and development under the 5G (5th generation) umbrella. According to a report²¹ published by IEEE 5G Initiative group, the following technologies are the key to 5G implementations and will affect both cellular and sensor networks as one unified internet of thing (IoT):

- Massive MIMO
- RAN Transmission cm and mm Waves
- New Waveforms
- Shared Spectrum Access
- Advanced Inter-Node Coordination
- Simultaneous Transmission Reception
- Multi-RAT Integration & Management
- D2D Communications
- Efficient Small Data Transmission
- Wireless Backhaul/Access
- Integration
- Flexible Networks
- Flexible Mobility
- Context Aware Networking
- Information Centric Networking
- Moving Networks

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